CHAPTER 11

New Product Design

11.1 Introduction

Chapter 1 defined five approaches for change. This chapter addresses the first approach to designing a new product or service. Competition for an existing product will increase with time. Today's technological innovations and changing markets make the development of new products and services competitive necessities. These developments can be new to the company or new to the market. Also, they could include additions to existing product lines or new applications of existing products. There is more opportunity for competitive advantage in product development than anywhere else.

Wheelwright and Clark (1992) published the major works on product development in the early 1990s. The development strategy relies on cross-functional integration of a design-build-test cycle through a sequence of development prototype testing: initial concept testing, design verification testing, design maturity testing, production verification testing, and volume production.

Kennedy (2003) describes in detail how Toyota's product development has high development productivity and innovation and low development cycle time, cost, and risk compared to a typical American company. Toyota creates knowledge by learning internally—knowledge cannot be purchased. Kennedy highlights some of Toyota's advantages:

- They have tremendous rigor on how they capture learning.
- Their knowledge gained from all previous projects is readily available and accessible.
- They do extensive prototyping at the subsystem level.
- They do not set hard specs at the start of a project.

- They do not establish an early system level design; instead they establish sets of possibilities for each subsystem.
- These sets consider all functional and manufacturing perspectives, building redundancy to risk while maintaining design flexibility.
- The final system design is developed through systematic combining and narrowing of these sets.
- New products more or less are allowed to emerge from the collective learning at the subsystem level.

Morgan and Liker (2006) describe Toyota's "set-based" concurrent engineering where multiple alternatives are examined simultaneously across functions. This dramatically increases the chances of arriving at an optimal solution as well as minimizing expensive engineering changes downstream.

Craig Barrett, Chief Operating Officer of Intel Corporation, says "You win the race by running faster. We're dedicated to obsoleting our own products before anyone else does. How quickly we get a product to market with features is what business is about."

As a foundation, organizations should consider adopting the following concepts in designing a new product:

- Upfront planning with increased learning in the design phase where the uncertainty is the greatest.
- Lots of protyping and testing to gain "live" knowledge required for decision making.
- Functions (marketing, engineering, and operations) tightly integrated and coordinated.
- Parallel, overlapping tasks instead of sequential or serial tasks.
- Small, dedicated teams with an enlarged scope of jobs.
- Focus on rapid learning by the teams.

These concepts along with the methods of planned experimentation (and systems thinking) will help improve communication, accelerate the learning, increase the leverage for higher quality products, and reduce the time necessary to bring the new product to market.

A starting point in the design of a new product is to identify the needs of the customer and generate ideas about a possible product or service. This was illustrated by Deming's production viewed as a system and the sequential building of knowledge using the Model for Improvement from Chap. 1.

Four phases for a new product design follow:

Phase 0: Generate ideas.
Phase 1: Develop concepts and define product.
Phase 2: Test the product.
Phase 3: Produce the product.

Figure 11.1 illustrates the major activities in each of the four phases by each of the major functions (marketing, engineering, and operations).

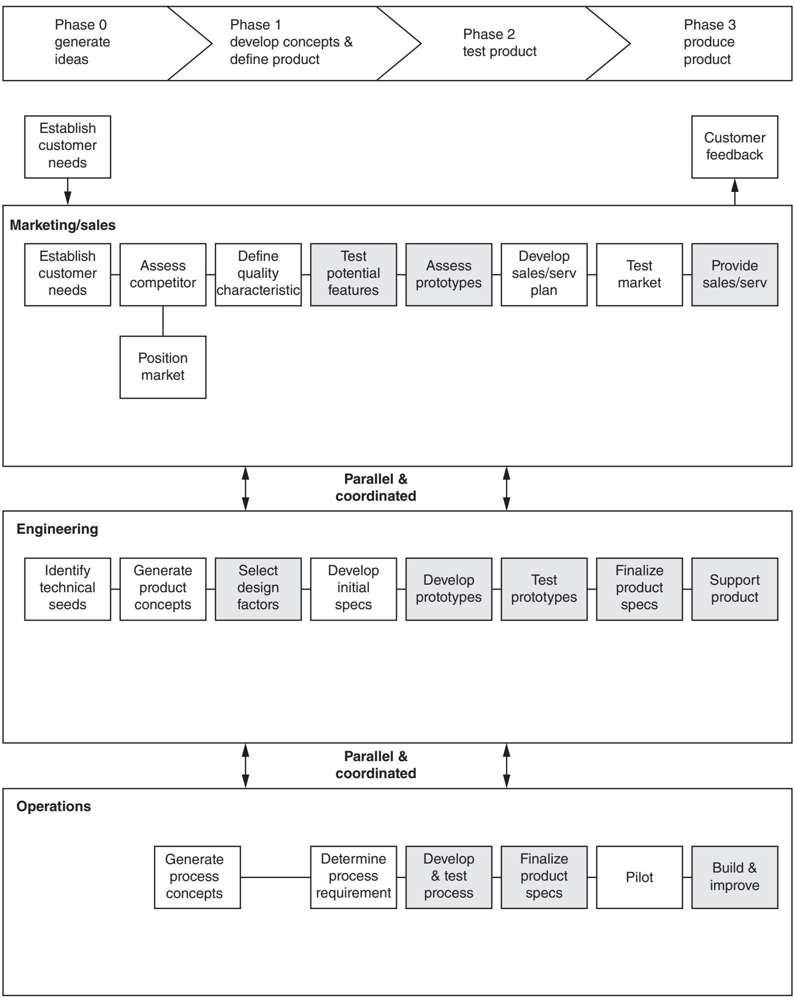


Figure 11.1 Four-Phase Process for New Product Design

Potential applications of planned experimentation are denoted by the shaded boxes in the figure.

The remaining sections of this chapter describe the activities in Fig. 11.1 and the use of the methods of planned experimentation in each phase. Lead functions are denoted by subheadings within each section of the chapter. The two examples illustrate the sequential nature of building knowledge toward the design of a new product (floor covering) and design of a new service (a training course) through the four phases.

11.2 Phase 0: Generate Ideas

Every successful product or service is based on satisfying a need of a customer or of society. Defining the need underlying a particular product or service is a major activity of this phase. How do customers use the product or service? Why is this product or service important to customers? What other product or service could be used instead?

Ideas about a product come from articulating the need. New ideas can come from: (1) direct search of opportunities involving marketing, R&D, and engineering; (2) exploratory consumer studies; (3) technology information (patents and inventions); (4) individual effort; and (5) creative group methods. It is important that several concepts are considered for the product.

Marketing

Marketing may conduct surveys to obtain information from people about their feelings, beliefs, experiences, needs, expectations, or wants. Survey methods include personal interviews, group interviews, written questionnaires, or simply observation of customers' use of your products (or your competitor's products). Recent marketing environments and trends should also be included in the analysis.

When planning a survey be explicit about what is to be learned from the survey. Questions must be asked in a way that the respondents can understand and answer. Test the questions with a small group of people who are representative of the anticipated respondents to the survey. Revise the questions based on this test. Segmentation of customer groups is determined by using the planned grouping tool of blocking of experimental units from Chap. 2.

Judgment samples are useful during the early stages of developing and testing a new product concept (analytic studies). Marketing books have recommended sampling strategies other than random sampling (probability samples). Dommermuth (1975) called these nonprobability samples “purposive samples.” Blankenship (1993) states, “Most samples chosen in marketing research are nonprobability samples. A true probability sample, because of the stringent requirements, is far too expensive and too time-consuming for most uses.” Johansson and Nonaka (1996) call this the “survey myopia” myth. They state, “Elaborate probability sampling designs are simply not necessary in marketing research.”

Once the needs to be satisfied are understood, quality can be defined by using a set of measures or quality characteristics that then serve as response variables for experiments conducted during the later phases. This translation of customer needs into quality characteristics is facilitated by a diagram called the quality characteristic diagram. The needs of the customer are listed at the top. The first column of the diagram defines quality at a primary level in the language of the customer. Examples are: easy to service, easy to close, does not rattle, proper size, lasts a long time, comfortable to use, does not skip, or easy to read. This primary level states how the product will give the customer what he or she wants.

The primary level of quality characteristics must be refined through more detailed steps, as illustrated by the additional columns (secondary and tertiary) of the diagram. Additional quality characteristics may be added by reviewing the supplier–customer measures defined in Chap. 1. The details of the quality characteristic should be measurable for comparison with competitive products. More detail can be attained by subdividing a quality characteristic into two or more subcharacteristics.

A weighting factor of some type for each quality characteristic (e.g., most important to least important or high, medium, and low) might provide useful information for potential tradeoffs later. Customer surveys may be necessary to justify the weightings.

Quality characteristics should be:

- Continuous variables, so far as possible.
- Measurable.

- A family of measurements that provides a definition of quality sufficient for the product.
- Specific enough to be useful for design of the product or process.

The quality characteristic diagram defines quality and provides a communication link for marketing, engineering, and operations. It provides these departments major input into the design of the product.

Example 11.1: Redesigning a Floor-Covering Product

A company that designs and manufactures floor coverings for home and commercial use has decided to replace an existing floor covering product with a more up-to-date line. Although the current product has been very successful over the past three years, marketing had defined some new colors and patterns that they believed would improve sales and customer satisfaction. The new product must wear well and be easy to clean as well as easy to install.

A product development team composed of marketing, R&D, engineering, and manufacturing personnel was formed to redesign the current floor-covering product. The first task was to define quality by identifying the quality characteristics for the new product. The quality characteristic diagram is given in Fig. 11.2.

Needs of the customer: Attractive floor that is easy to care for		
	Quality characteristics[1]	
Primary[2]	**Secondary[3]**	**Tertiary[3]**
Looks good	Consistent with fashion trends	
	attractive	
	lack of visible seams	
Easy to clean	Time to clean	
	Effort to clean	
Wears well	Resistance to scratches	
	Stain resistance	
	Gloss retention	

[1]Do not include design factors in this list. (*Test:* You should *not* be able to set the levels of these quality characteristics.)
[2]Express in the language of the customer.
[3]To add more detail, subdivide into two or more quality characteristics.

Figure 11.2 Quality Characteristic Diagram for Redesigning Floor Covering

Engineering

People in engineering (or R&D) must have a deep understanding of new technologies and materials and an independent drive for creativity. They must be given the freedom to take risks and learn from their failures. The improvement cycle and planned experimentation will be important methods to maximize learning. Outcomes of this process include an increased understanding of new technologies and materials and concepts for new products based on these technologies.

Sometimes a new technology leads to the expansion of old concepts for new products. Miniaturization of the microchip is an example. New technology is generated by a combination of needs, concepts, and hardware. There must be sufficient activity addressing all major strategic needs of the customer.

Sometimes a new product or process idea does not require or warrant new technology. The capacity to generate technology is important, but the challenge is to bring the technology to the marketplace with lower cost and higher quality.

What are the product possibilities? How well can they be manufactured? What is their potential in meeting the needs of the customer? The table given in Fig. 11.3 captures important information for new and current concepts. When generating product concepts, the selected concepts must be capable of meeting the customer's needs through products that

Product concept	Product form/ structure	Ease in manufacturing assembly	Needs addressed	Potential risk in meeting needs low/medium/high
(Current)				
(New)				

Figure 11.3 Assessment of Product Concepts

1. Objective: Select a product concept from available candidates.		
2. Background information: Information on each product concept that is in contention. (Fig. 11.3)		
3.	**Experimental variables:**	
A.	**Response variables**	**Measurement technique**
	1. Quality characteristics	(may be subjective rankings)
	2. Manufacturability measures • Assembly time • Number of parts, steps • Manufacturing costs 3. Life in service	(may be subjective rankings)
B.	**Factors under study**	**Levels**
	1. Product concept	Current New 1 New 2
C.	**Background variables**	**Method of control**
	1. Wide range of conditions (production and customer)	(consider chunk-type block variables)
4. Experimental unit: Prototype build		

Figure 11.4 Example of a Planning Form for Selecting a Product Concept

can be easily manufactured and assembled. Assessment of process concepts can be done by the table as well.

Identify several conceptual designs and the form or structure that the product might take. Avoid selecting one concept without serious consideration of others. Screen product concepts while increasing current knowledge by running planned experiments to reduce the number of conceptual designs. An example of a planning form using a randomized block design for the selection of a product concept is given in Fig. 11.4.

Operations

The generation of new ideas to be used for manufacturing a new product should follow the same process as engineering. Consideration should be given to modular design, number of assembly steps, assembly time, material cost and availability, and automation.

11.3 Phase 1: Develop Concepts and Define Product

Marketing

How are the best concepts or features in a new product selected for meeting customer needs from the many that are in contention? Marketing research is faced with the task of providing answers to that question. Methods used to help answer this question include sampling, surveys, and experimental design. Kano surveys (Kano, 1994) and conjoint analysis (consider jointly) are frequently mentioned as methods for testing multiple new product features. These methods are used with different customer groups that possess the needs identified in Phase 0.

Example 11.1 (Continued): Conjoint Analysis on Potential Features for New Floor Covering

The marketing research group from a manufacturer of floor covering has identified several potential features for a floor-covering product. The planning form is given in Fig. 11.5. The response variable is an average ranking (ordinal measurement) by the potential customers. Profile cards are prepared with each combination of factor combinations in the eight tests of the 2^{7-3} fractional factorial design. Pictures of the different combinations of colors and patterns of floor covering were included on the profile cards.

An example of a profile card for Condition 1 of the design matrix (− − − + + + −) is given below:

Profile A:
Current price [Picture with current pattern, standard installation instructions, no cleaning kit, new color family, vinyl coating , and gloss finish]

Figure 11.6 shows the results of the study. The response variable is average rank, with lower rank being better (most appealing). On the dot diagram, a negative effect means that moving from the − to + level increased the appeal by having that feature. Coating, color, and pattern were the most appealing features. Price had a positive effect, meaning that people were unwilling to pay for additional features. An interaction of price with a feature could indicate a willingness to pay for that feature.

1. Objective:
Determine what features to offer in a product profile.

2. Background Information:
The team has identified several potential features for the new floor covering.

3. Experimental Variables:

A.

Response variables	**Measurement technique**
1. Ranks (most appealing to least)	Average ranking of 8 product profile cards by 25 potential customers

B.

Factors under study	**Levels**	
1. Pattern	current	new
2. Installation instruction	standard	video
3. Cleaning kit	no	yes
4. Color family	old	new
5. Coating	acrylic	vinyl
6. Gloss finish	no	yes
7. Price	current	5% increase

C.

Background variables	**Method of control**
1. Age of customer	Create 2 blocks
2. Income of customer	Create 2 blocks
3. All others	Hold constant

4. Experimental Unit: Product profile card

5. Replication: Each of the 8 profile cards will be ranked by 25 customers in each of the 4 blocks.

6. Methods of randomization: Shuffle the order of the 8 profile cards.

7. Design matrix: (attach copy) 2^{7-4} design with 8 runs.

8. Data collection forms: (attach copies) Form in the customer packet.

9. Planned methods of statistical analysis: Dot diagram and response plots for each block

10. Estimated cost, schedule, and other resource consideration: Total cost for this experiment is $15,000. Customers within each block will be participating in an evening session. All 4 sessions will be completed in 1 week.

Figure 11.5 Planning Form for Conjoint Analysis for Floor Covering

Based on the analysis and the current knowledge, the following conclusions are:

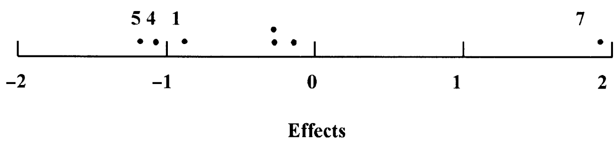
- Price was important (not willing to pay for additional features).
- Vinyl coating was preferred.
- New color and patterns were preferred.

A methodology that brings marketing, engineering, and operations together to plan the product is quality function deployment (QFD). QFD relates the factors for design to the quality characteristics identified in Phase 0.

Design matrix for a 2^{7-4} pattern

Test	Run order	1	2	3	4	5	6	7	Average rank
		24	14	15	12	13	23	34	
		35	36	26	56	46	45	25	
		67	57	47	37	27	17	16	
1	6	–	–	–	+	+	+	–	2.9
2	3	+	–	–	–	–	+	+	6.1
3	8	–	+	–	–	+	–	+	6.0
4	5	+	+	–	+	–	–	–	3.4
5	1	–	–	+	+	–	–	+	5.9
6	7	+	–	+	–	+	–	–	3.1
7	2	–	+	+	–	–	+	–	4.6
8	4	+	+	+	+	+	+	+	3.5
Effects:		–0.8	0.1	–0.3	–1.0	–1.1	–0.3	1.9	

Dot diagram of effects



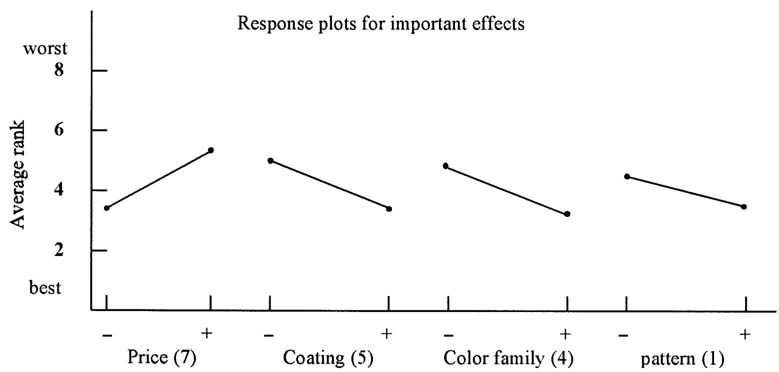


Figure 11.6 Design Matrix, Dot Diagram, and Response Plots for Floor Covering

In its most basic form QFD can be thought of as matrix with the rows representing the customers' needs (the "whats") and the columns representing the design aspects of a new product(the "hows"). At the intersections of the matrix, symbols are used to represent the degree of relationship between the rows and columns. Additional features may be added to the matrix. The relationships between the columns (design factors) can be added to the top of the columns. Analysis of competitors can be added to the right-hand column. Best settings or targets of the design factors can be added at the bottom of the columns.

QFD links the four major phases in the design of a new product. Constant interaction between marketing, research, engineering, manufacturing, and sales/service is needed to translate the needs of the customer into a new or improved product that will better meet those needs. QFD promotes this interaction and the breaking down of barriers between departments. See Hauser and Clausing (1988) and Akao (1990) for more discussion on QFD.

Multiple QFD matrices may be used to help plan the entire product design process from design characteristics to product specifications to process specifications. Each set of columns becomes the set of rows for the next lower-level relationship.

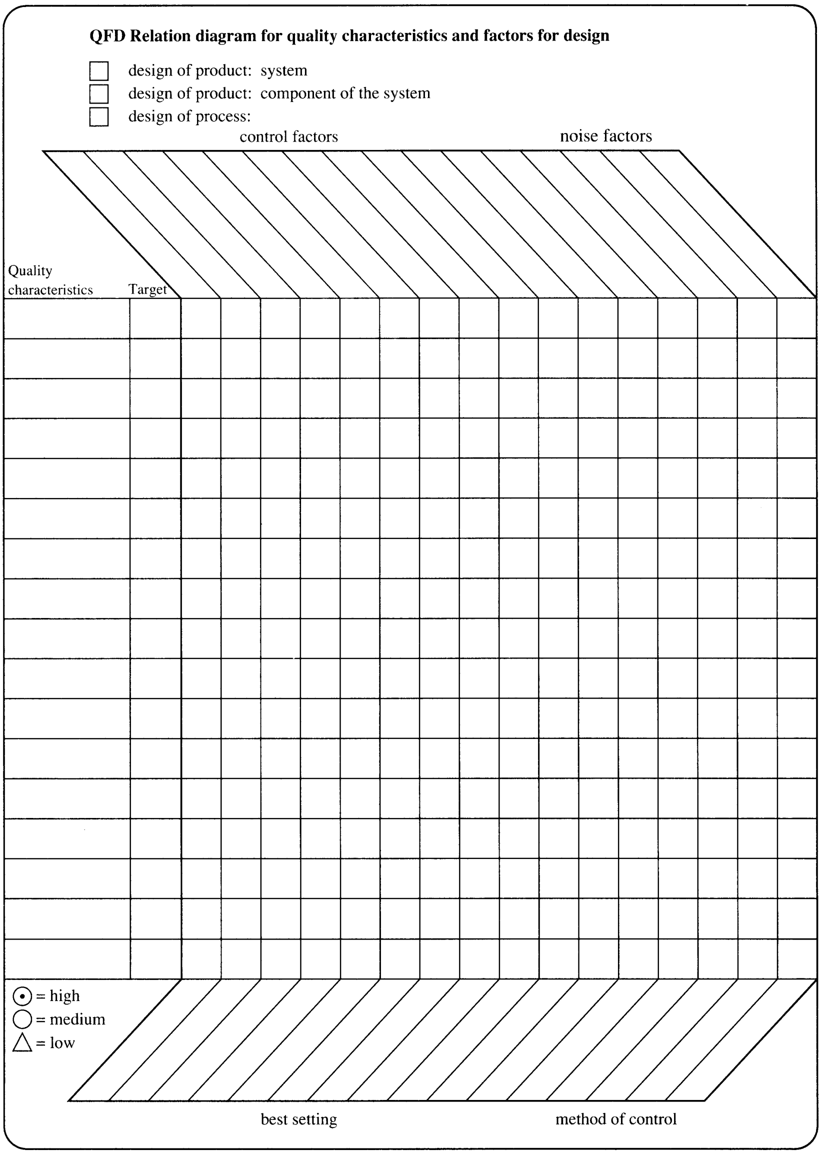
Engineering

A diagram modifying the matrix of QFD is illustrated in Fig. 11.7. The QFD relation diagram provides the product designers with a method for relating quality characteristics to factors that should be addressed in the design of a new product or component. This diagram helps define the current knowledge for a product and is analogous to a cause-and-effect diagram.

The extreme left-hand column of the QFD relation diagram lists the quality characteristics that have been identified using the quality characteristic diagram. Quality characteristics are used as response variables in planned experimentation to increase product knowledge. When there are multiple measurements of the quality characteristic at the same combination of levels of the factors, it is often useful to form several statistics. The overriding factor in selection of a quality characteristic statistic is its impact on customer loss and its relationship to customer need. Following is a discussion of some commonly used statistics:

Average

The average of the observations in the experiment reduces the magnitude of variation due to nuisance variables. The average is widely used as a response variable when replication is included in the design.



What planned experiments need to be run to test this diagram?

Figure 11.7 QFD Relation Diagram

Standard Deviation

The standard deviation of the observations in a replicated experiment represents the magnitude of the nuisance or background variables within the experimental pattern. Ranges could be used instead of standard deviation if the number of observations is small (less than ten) and constant for each factor combination.

Average Versus Variation

Both average and measures of variation such as standard deviations could be used as response variables. The choice depends on the relative impact of each on customer loss. The objective is to minimize the loss to customer.

Taguchi (1987) uses a signal-to-noise ratio consisting of an average (signal) divided by some measure of variation (noise) as a response variable. This signal-to-noise ratio has no advantage as a response variable over looking at average and variation separately, and it is more difficult to interpret.(See Box(1988) for more discussion on signal-to-noise ratios.)

Once the statistic of the quality characteristic is defined, the target value for each statistic is determined. The target value is in the second column. There are three cases of the target value (t):

1. Smaller is better ($t = 0$): wear, shrinkage, deterioration.
2. Bigger is better ($t =$ infinity): strength, life, fuel efficiency.
3. Target value is best ($t = t_o$): dimension, clearance, weight, viscosity.

This target is set at minimum loss to the customer. Figure 11.8 gives examples of needs, quality characteristics, selected statistics of quality characteristics, and target values from examples presented in earlier chapters of this book.

Need of the customer	Quality characteristic	Statistic of the quality characteristics	Target values	Example in book
Increased tool-life	wear rate	slope of line	smaller	3.3
Labels on cans	lables loose or not	percent cans with loose labels	smaller	3.5
Color	shade	shade reading	200	4.2
Smoothness of finished part	microfinish	average	smaller	9.1

Figure 11.8 Examples of Quality Characteristics and Target

The remaining columns of the QFD relation diagram are factors that may have an effect on the quality characteristic. These factors are classified as control factors and noise factors and are defined as follows:

Control factors: Factors that can be assigned at specific levels. These factors are set by those designing the product; they are not directly changed by the customer.

Noise factors: These factors can potentially affect the quality characteristic but cannot be controlled at the design phase. There are three types of noise factors (Taguchi, 1987). They are external factors (the environment in which the product is used or distributed), internal factors (product deterioration with age or use), and unit-to-unit factors (variations in the manufacturing process).

An example of control factors when designing a new tennis racket would be the shape of the frame and the type of composite material selected for the frame. Examples of noise factors include temperature or humidity (external), wear or warp of the frame (internal), and the effect of variation in shape of different frames on accuracy of how the racket strikes the ball (unit-to-unit).

These three sources of noise must be considered during the early phases of product design. Figure 11.9 illustrates how product performance variation can be reduced (based on Kackar, 1985).

The leverage for improvements during the early phases in the product cycle is many times greater than for improvements made during actual production of that product. When an engineer calls for changes early in product design, there is time to make improvements at the lowest cost. The majority of the production costs, including levels of scrap, are determined during the design of the product and the design of the production process.

Process/noise:	External	Internal	Unit-to-unit
Design of product	high	high	medium
Design of production process	low	medium	high
Production	low	low	medium
Sales/service	medium	low	low

Figure 11.9 Leverage on Noise Factors to Reduce Variability

At the bottom of the QFD relation diagram is the best setting for each of the control factors and method of control for each noise factor. These are determined by running planned experiments with selection of the experimental variables in the following way:

Response variables = quality characteristic
Factors under study = control factors and noise factors
Background variables = noise factors

Although the above relationships are the general rule, there will be some exceptions. For example, inner noise factors such as wear may be used as response variables. As more knowledge is gained from planned experiments, the QFD relation diagram should be updated for relationships between factors and quality characteristics, best settings for control factors, and method of control of noise factors.

Another powerful strategy for improving product at this early phase is *robust* design. Planned experiments are used to test the interactions between control factors and noise factors. The strategy is to take advantage of an interaction by setting a control factor a level that desensitizes the noise factor. For example, suppose an engineer is considering different materials for brake pads to improve brake torque. The noise factor is the temperature of the pads during various driving conditions. Figure 11.10 displays the interaction plot of the control factor (pad material) and the

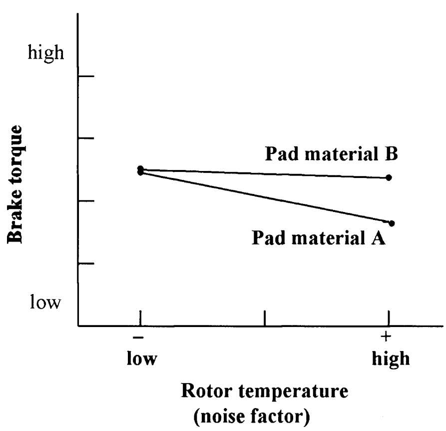


Figure 11.10 Interaction of a Control Factor and a Noise Factor

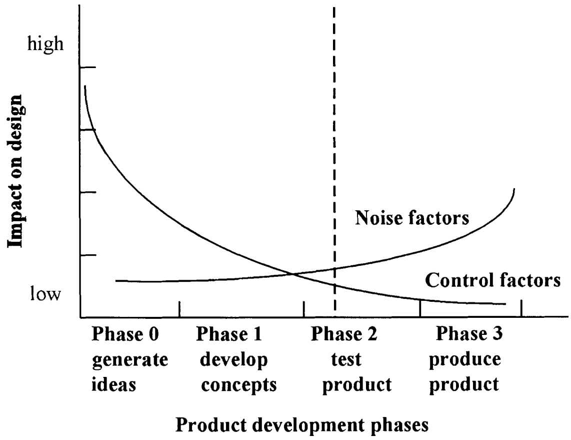


Figure 11.11 Leverage for Achieving Robust Design

noise factor (rotor temperature). The strategy for robust design would be to go with pad Material B.

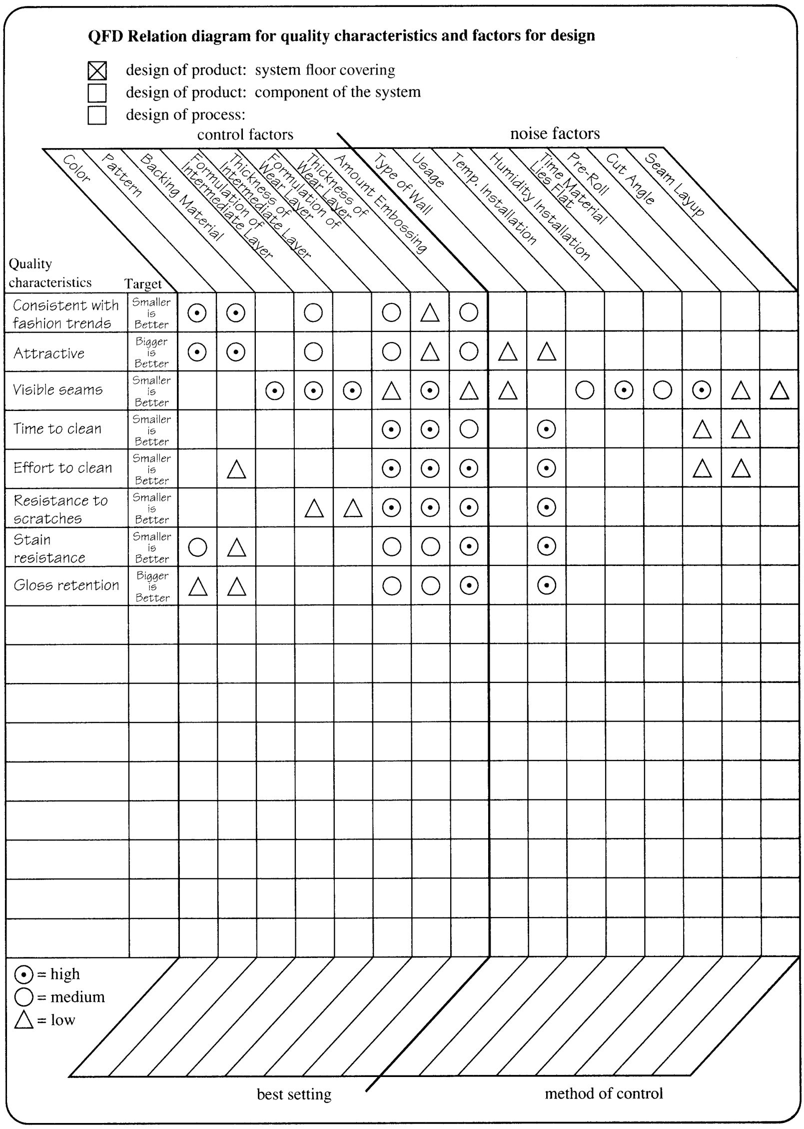
The overall strategy of robust design is to set control factors to desensitize the product or process to noise factors requires a change from thinking about designing a product or process as a search for something that works. The leverage of achieving robustness upstream is illustrated in Fig. 11.11.

The QFD relation diagram is useful in planning the types of experiments that are needed to decide the best settings for control factors to ensure that the quality characteristics will be close to the target (minimum loss) and have minimum sensitivity to the noise factor.

Example 11.1(Continued): Setting of Control Factors for New Floor Covering

The product development team from a manufacturer of floor covering identified the factors for design of a vinyl-coated floor-covering product. Figure 11.12 provides the QFD relation diagram.

The team has a moderate level of knowledge that the new design will be perceived as more attractive. Previous tests have identified a seam problem because of shrinkage of the floor covering (probably due to temperature or humidity during installation). When two sheets were put together, the seam tended to show. When the width of the seam was greater than 0.2 mils,



What planned experiments need to be run to test this diagram?

Figure 11.12 QFD Relation Diagram for the Floor-Covering Experiment

it called attention to the seams and detracted from the appearance of the floor.

The group decided to determine the effect that installation factors have on seams and appearance. It was hoped that by setting control factors,

1. Objective: Find the best settings of the control factors to minimize visible seams while preserving the appearance.		
2. Background Information: The redesign has a new color and pattern that has a beautiful appearance. There has been a problem with seams. Probable cause is temperature or humidity at the installation site.		
3. Experimental Variables:		
A.	**Response variables**	**Measurement technique**
	1. Visible seams	gage (mils)
	2. Appearance	subjective scoring
B.	**Factors under study**	**Levels**
	1. Backing material	Material A Material B
	2. Formulation of intermediate layer	Formula 1 Formula 2
	3. Thickness of wear layer	1.0 mils 2.0 mils
	4. Temperature/humidity	50°/40% 90°/80%
	5. Preroll	0 min. 10 min.
C.	**Background variables**	**Method of control**
	1. Installer	One person, standard instructions
	2. Subfloor	Use plywood
	3. All others	Use standard for all applications
4.	**Experimental Unit:** Prototype	
5. Replication: Four measurements for visible seams per piece		
6. Methods of randomization: Order of the 16 runs was randomized		
7. Design matrix: (attach copy) 2^{5-1} factorial design		
8. Data collection forms: (not show here)		
9. Planned methods of statistical analysis: Dot diagrams and response plots		
10. Estimated cost, schedule, and other resource consideration: Evaluated in the test room with temperature and humidity controls. Four days are required to complete. Appearance scoring done by appearance team.		

Figure 11.13 Documentation of the Floor Covering Experiment

noise factors would be reduced. Figure 11.13 contains the planning form for the study.

Three control factors and two installation (noise) factors were studied. Four measurements were made on each seam and averages and standard deviations were calculated. A large standard deviation would show up as variation in seam width. A 2^{5-1} design was chosen because there is no confounding of two-factor interactions with main effect.

Appearance of the new design remained good throughout the 16 runs of the experiment. Laboratory testing for scratches, stains, and gloss retention confirmed that no deterioration took place for these quality characteristics.

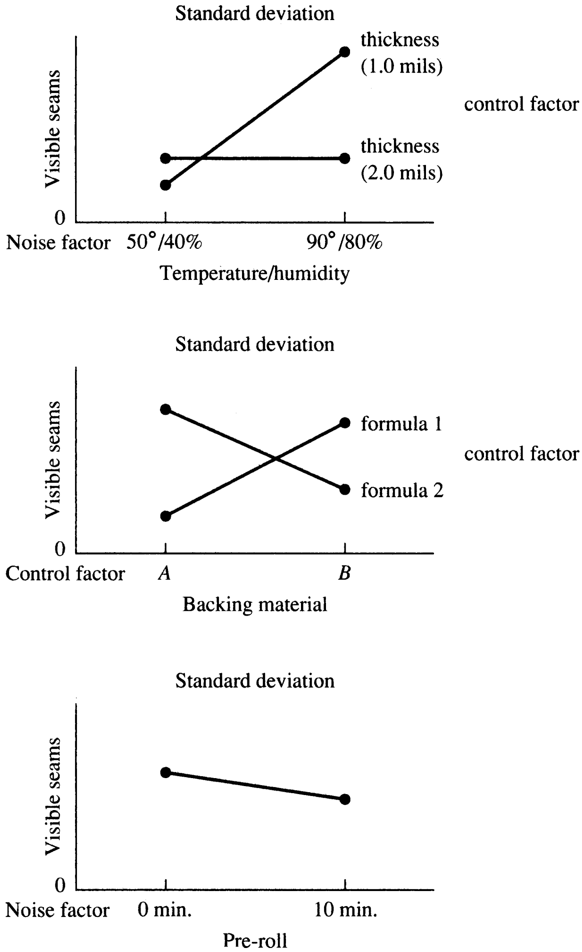


Figure 11.14 Response Plots for the Floor-Covering Experiment

Figure 11.14 contains the response plots for standard deviations of visible seams: they summarize the important results of the experiment. The first plot shows a strong interaction between a control factor and a noise factor. Thickness of wear level interacts with the temperature/humidity noise factor. The effect of this noise factor on visible seams is less with the 2.0 mil wear layer. The thinner wear level (1.0 mil) was affected by a high temperature/humidity combination.

The second plot shows a strong interaction between the other two control factors. Backing material and the formulation of the intermediate layer interacted with respect to seams. Both backing materials are needed for different applications. Thus, Material A is chosen with Formula 1, and B is chosen with Formula 2.

The third plot demonstrates a strong relationship between an installation factor and visible seams. By laying out the roll for 10 min before installation, the seams will have less variation. This adds to the installation time.

Based on these analyses and the current knowledge, the following conclusions (and updates for Fig. 11.12) are:

Control factors	Best setting
Thickness of wear layer	2.0 mils
Backing material	A with Formula 1
	B with Formula 2
Noise factors	**Method of control**
Preroll	Have installation instructions
	Include a preroll at 10 min
Temperature/humidity	Desensitized by setting control factor, thickness of wear layer, at 2.0 mils

The objective of the next PDSA Cycle for the team is to plan an experiment to select factors for design that have an effect on the quality characteristics.

The plan for this cycle is to vary the formulation of intermediate and wear layers to simulate the current and new product. The belief is that the humidity during installation may be interacting with the new product and causing the seam problem. The planning form is given in Fig. 11.15. The design matrix is given in Fig. 11.16.

The run charts for the averages and standard deviations of visible seams at each of the 16 combinations are contained in Fig. 11.17. No obvious patterns were present. Three of the points on the average chart obviously indicate special causes. Further analysis will disclose that those points were due to changing the factors under study.

1. Objective: Find the best settings of the control factors to minimize visible seams while preserving the appearance.

2. Background Information: The redesign has a new color and pattern that has a beautiful appearance. There has been a problem with seams. Probable cause is temperature or humidity at the installation site.

3. Experimental Variables:

A.

Response variables	**Measurement technique**
1. Visible seams	Gage (mils)
2. Appearance	Subjective scoring

B.

Factors under study	**Levels**	
1. Backing material	Material A	Material B
2. Formulation of intermediate layer	Formula 1	Formula 2
3. Thickness of wear layer	1.0 mils	2.0 mils
4. Temperature/humidity	50°/40%	90°/80%
5. Preroll	0 min.	10 min.

C.

Background variables	**Method of control**
1. Installer	One person, standard instructions
2. Subfloor	Use plywood
3. All others	Use standard for all applications

4. Experimental Unit: Prototype

5. Replication: Four measurements for visible seams per piece

6. Methods of randomization: Order of the 16 runs was randomized

7. Design matrix: (attach copy) 2^{5-1} factorial design

8. Data collection forms: (not show here)

9. Planned methods of statistical analysis: Dot diagrams and response plots

10. Estimated cost, schedule, and other resource consideration: Evaluated in the test room with temperature and humidity controls. Four days are required to complete. Appearance scoring done by appearance team.

Figure 11.15 Documentation of the Floor-Covering Experiment

The effects of the factors computed from the design matrix were included in Fig. 11.16. The dot diagrams are contained in Fig. 11.18.

One control factor (formulation) and three noise factors (preroll, humidity, and temperature)were found to be important. Temperature was a real surprise. It was thought that humidity was the problem.

Analysis of the two cubes from Fig. 11.19 (see also Fig. 11.20) as a full factorial design indicates a possible interaction between formulation and temperature for averages. These interactions accounted for the three high points on the run chart for averages in Fig. 11.17.

Test	Run order	1 F	2	3 T	4 H	5	6 P	7	8	12 37 56 48	13 27 46 58	14 36 57 28	15 26 47 38	16 25 34 78	17 23 45 68	24 35 67 18	Response Average	Response Standard deviation
1	8	–	–	–	+	+	+	–	+	+	+	–	–	–	+	–	0	4
2	15	+	–	–	–	–	+	+	+	–	–	–	–	+	+	+	11	11
3	16	–	+	–	–	+	–	+	+	–	+	+	–	+	–	–	4	5
4	6	+	+	–	+	–	–	–	+	+	–	+	–	–	–	+	4	5
5	3	–	–	+	+	–	–	+	+	+	–	–	+	+	–	–	9	12
6	12	+	–	+	–	+	–	–	+	–	+	–	+	–	–	+	42	18
7	9	–	+	+	–	–	+	–	+	–	–	+	+	–	+	–	5	5
8	7	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	77	14
9	1	+	+	+	–	–	–	+	–	+	+	–	–	–	+	–	18	11
10	4	–	+	+	+	+	–	–	–	–	–	–	–	+	+	+	21	10
11	10	+	–	+	+	–	+	–	–	–	+	+	–	+	–	–	80	25
12	13	–	–	+	–	+	+	+	–	+	–	+	–	–	–	+	12	9
13	11	+	+	–	–	+	+	–	–	+	–	–	+	+	–	–	9	5
14	2	–	+	–	+	–	+	+	–	–	+	–	+	–	–	+	2	4
15	14	+	–	–	+	+	–	+	–	–	–	+	+	–	+	–	1	8
16	5	–	–	–	–	–	–	–	–	+	+	+	+	+	+	+	1	2
Divisor = 8																		
	Average	23.5	−2.0	29	11.5	4.5	12.0	−3.5	2.0	−4.5	19.0	10.4	−0.5	16	−3.5	5.5		
	Standard deviation	5.8	−3.8	7.5	2.0	−0.2	0.8	0.1	0	−3.0	2.2	−0.2	−1.5	2.5	−2.8	−0.2		

Figure 11.16 2^{8-4} Design Matrix for the Floor-Covering Experiment

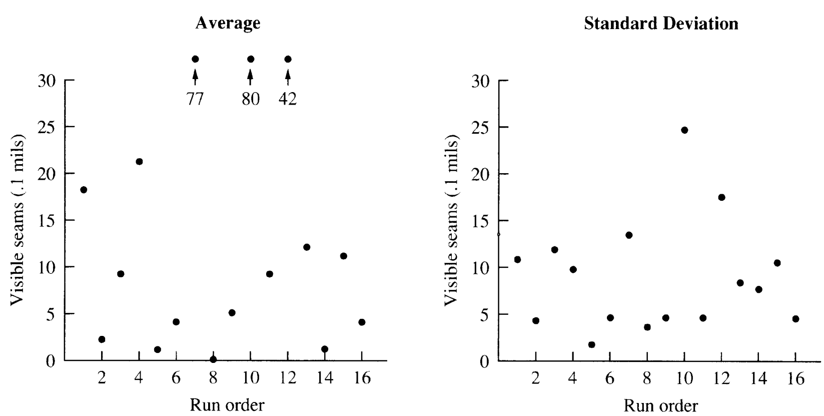


Figure 11.17 Run Charts for the Floor-Covering Study

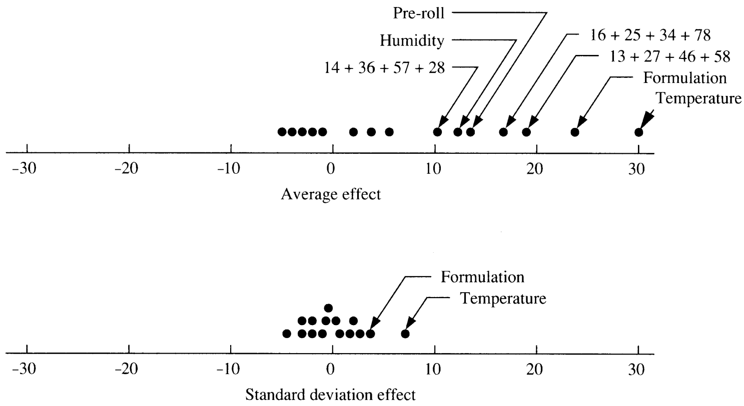


Figure 11.18 Dot Diagrams for the Floor-Covering Study

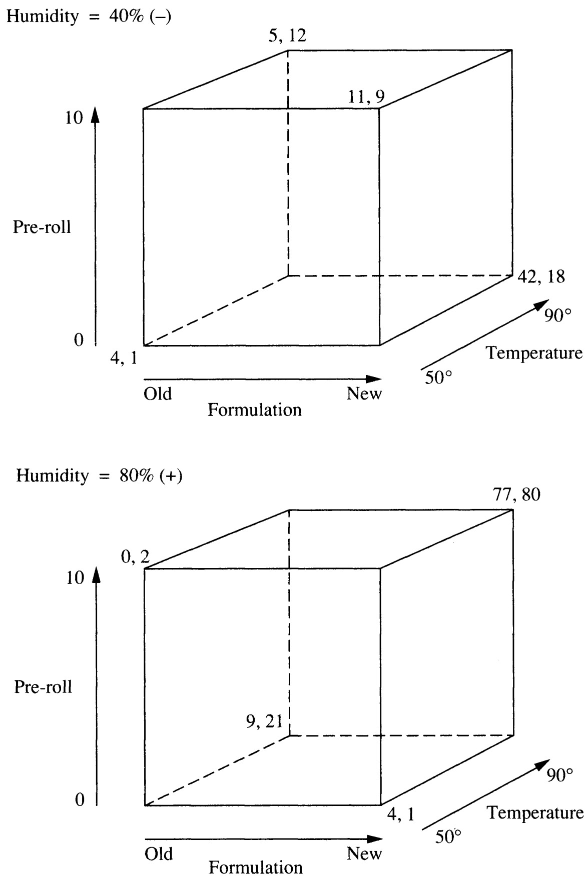


Figure 11.19 Cube for the Floor-Covering Experiment (2^{8-4} Design, Any Three Factors Form a Full Factorial Design)

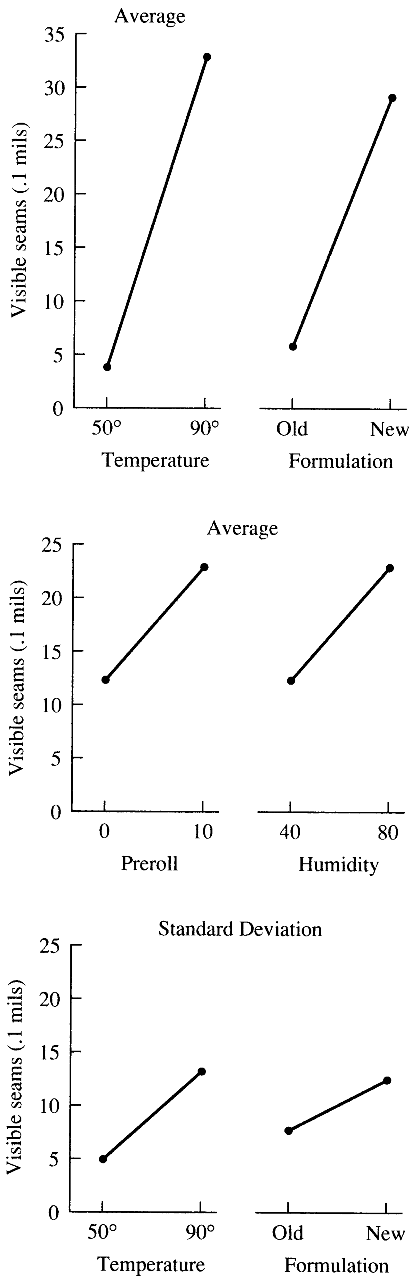


Figure 11.20 Response Plots for Important Effects for the Floor-Covering Experiment

Example 11.2: Designing a New Service

A new course in planned experimentation is being designed. What are the needs of the customer and the corresponding quality characteristics that guide the design of this new course?

Figure 11.21 contains the quality characteristic diagram. This course should create an enjoyable learning experience for the students. It is also

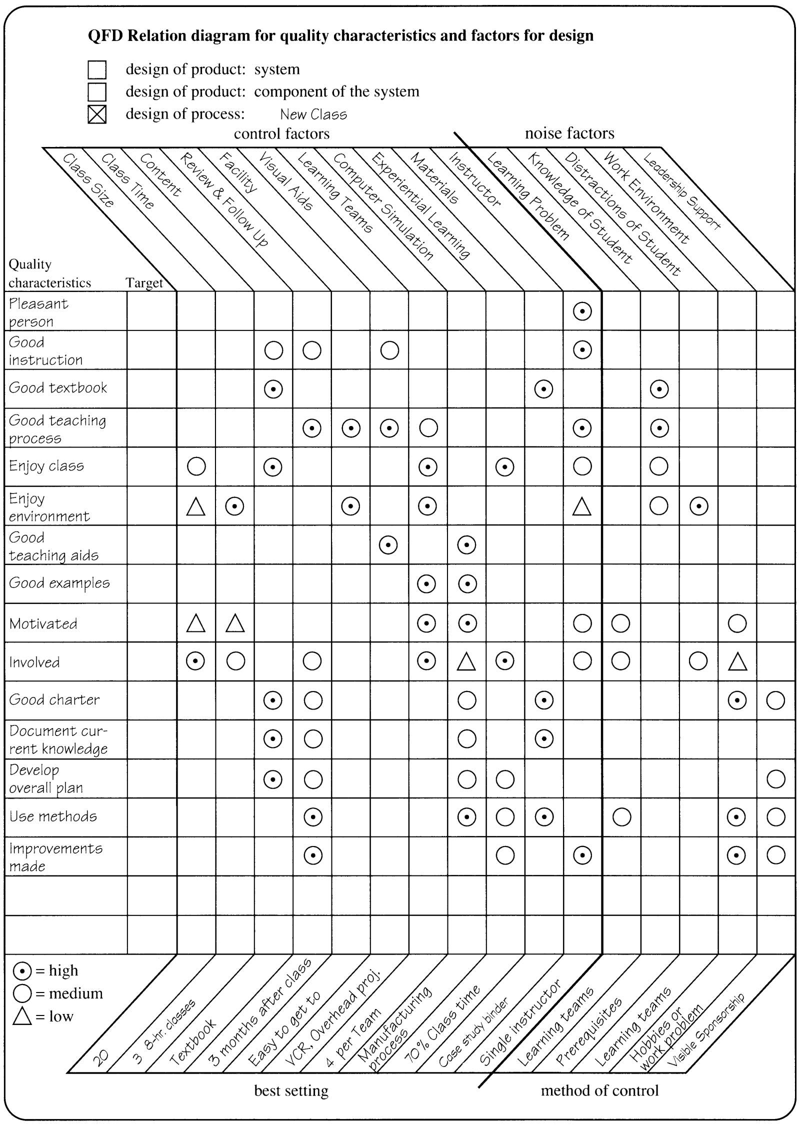
Needs of the customer: Enjoy learning new concepts and be able to apply concepts to job or hobby.

Quality characteristic[1]			
Primary[2]	**Secondary**[3]	**Tertiary**[3]	**#**
Enjoy instruction	Good teacher	Pleasant person	1
		Good instructor	2
	Good class	Good textbook	3
		Good teaching process	4
Enjoy learning	Have fun in class	Enjoy class	5
		Enjoy environment	6
	Clear instruction	Good teaching aids	7
		Good examples	8
	Interesting	Motivated	9
		Involved	10
Recognize applications	Problem clear	Good charter	11
	Formulate problem	Document current knowledge	12
		Develop overall plan	13
Know how to use methods successfully	Use improvement cycle	Use methods	14
		Improvements made	15

[1] Do not include design factors in this list. (*Test*: You should *not* be able to set the levels of these quality characteristics.)
[2] Express in the language of the customer.
[3] To add more detail, subdivide into two or more quality characteristics.

Figure 11.21 Quality Characteristic Diagram for Designing a Course in Planned Experimentation intended to enable them to apply the concepts to their jobs or hobbies. Fifteen quality characteristics were identified as important measures for this class.

What are the control factors in designing this new course? What are the noise factors? The QFD relation diagram is given in Fig. 11.22. Eleven



What planned experiments need to be run to test this diagram?

Figure 11.22 QFD Relation Diagram for Designing a Course in Planned Experimentation control factors are identified based on concepts developed from various sources of adult education research. The control factor "learning teams" relates to many of the quality characteristics. The five noise factors may affect the learning.

How can the noise factors be desensitized or eliminated? Best settings of control factors are based on experimenting with related classes. The method of control for noise factors has proved successful in other classes.

What is the best setting (team size and makeup) for the control factor learning teams? A planned experiment for a prototype class can help answer this question. Figure 11.23 gives an example of the planning form for such an experiment.

Example 11.2 involved designing a new service rather than a new product. Inspection can prevent a bad product from reaching the customer,

1. Objective: Select size and makeup of a learning team for a planned experiment class		
2. Background Information: Previous classroom experience with teams and a literature search on cooperative learning teams		
3. Experimental Variables:		
A.	**Response variables**	**Measurement technique**
	1. Concepts learned	Test
	2. Enjoyed class	Interview
	3. Involved	Observation
B.	**Factors under study**	**Levels**
	1. Size of team	5 8
	2. Makeup of team	Matched Diverse
C.	**Background variables**	**Method of control**
	1. Learning disability	Measure
	2. Knowledge of student	Chunk-type block variable
	3. Distraction of student	Chunk-type block variable
4. Experimental Unit: Student team		
5. Replication: Four replications (four blocks as noise factors) will be made using the four combinations of the two factors under study.		
6. Methods of randomization: Randomize the four combinations of the two factors.		
7. Design matrix: (attach copy) 2^2 design in four blocks		
8. Data collection forms: (attach copies) (not shown here)		
9. Planned methods of statistical analysis: Dot diagram and response plots of test scores		
10. Estimated cost, schedule, and other resource consideration: Run during a four-day course on planned experimentation.		

Figure 11.23 Documentation of an Experiment to Study Learning Teams

but this is often not possible for a service. It is too late; the service to the customer has already been provided. Since this is the case in designing a class, achieving quality by the design is very important.

Operations

As product designers of engineering are developing prototypes and initial product specifications, operations (manufacturing engineering) should determine process requirements to produce the product. Also, the strategy for robust design deployed by engineering will be applied by operations in the next phase.

11.4 Phase 2: Test

How is a new product designed to work under a wide range of conditions that will be encountered during actual production and use by the customer? The strategy of robust design continues as all three functions address the question in this phase.

Marketing

With a better definition of the product, marketing should continue their testing with customer groups. This will help fine-tune the product to target customers. Experiments with focus groups could be run to assess the reaction of the current prototypes and some of the leading competitor's products as factors under study.

Example 11.2 (Continued): Testing a New Service

Based on the QFD relation diagram in Fig. 11.22, a focus group of ten students were chosen to assess potential semester courses. Figure 11.24 contains the planning form. A 2^3 design resulted in eight potential class descriptions, A through H. These descriptions were given to each member of the focus group and asked to rank them best (1) to worst (8). Figure 11.25 provided a data collection form. Both average ranks and standard deviation of ranks were calculated for the eight class descriptions.

1. Objective: Test scheduling options and classroom exercises for a new planned experiment class

2. Background Information: Several three-days per week semester classes have been taught in the past with many students complaining about the commuting time required to attend a one hour class. Also, hands on exercises were more popular than giving homework assignments for the exercises at the end of the chapters. Continuing education classes of 5 full days have been popular especially using a computer simulation game called "Midstate Brick Factory." This program allows the user to design and run various planned experiments available in the textbook.

3. Experimental Variables:

A.

Response variables	**Measurement technique**
1. Average rank	Average ranks of 20 students
2. Standard deviation of ranks	Standard deviation of ranks of 20 students

B.

Factors under study	**Levels**	
1. Exercises	simulation	end of chapter exercises
2. Learning style	individuals	teams
3. Class frequency	M-W-F (1 h)	M (3 h)

C.

Background variables	**Method of control**
1. Working students	Hold constant: students with a job
2. Knowledge of student	Required prerequisites
3. Distraction of student	Observed and recorded

4. Experimental Unit: Student

5. Replication: Twenty working students are selected based on their major and interest in the course in the next 2 years.

6. Methods of randomization: Randomize the eight combinations of the potential course to the 20 students.

7. Design matrix: (attach copy) 2^3 factorial design

8. Data collection forms: (attach copies) (see Fig. 11.25)

9. Planned methods of statistical analysis: Response plots of average and standard deviation of ranks for the 20 students.

10. Estimated cost, schedule, and other resource consideration: Run during registration week. Each student can complete the ranking of the 8 combinations in 15 min.

Figure 11.24 Planning Form for Testing a New Course

The design matrix and response plots for average ranks are given in Fig. 11.26. There is a strong interaction between learning style and exercises. The preferred course was a team structure using the simulation instead of end-of-chapter exercises. However, if end-of-chapter exercises were used, the students preferred to work as individuals.

Although the average rank did not reveal a strong effect due to class frequency, the standard deviation of ranks revealed a different story. This can be seen from the design matrix and response plots given in Fig. 11.27. The strong effect came from class frequency. If the class frequency was

Course	Combination	Data (1 = best)
D	Chapter exercises, no student teams M-W-F (1 h)	Rank =
H	Chapter exercises, no student teams M (3 h)	Rank =
F	Chapter exercises, with student teams M (3 h)	Rank =
C	Computer simulation, no student teams M-W-F (1 h)	Rank =
E	Computer simulation, with student teams M (3 h)	Rank =
G	Computer simulation, no student teams M (3 h)	Rank =
A	Computer simulation, with student teams M-W-F (1 h)	Rank =
B	Chapter exercises, with student teams M-W-F (1 h)	Rank =

Figure 11.25 Data Collection Form for Testing a New Course

	–	Simul	Teams	3day 1hour					
	+	Ch exer	Individual	1day 3hour					
Test	Run order	Exercises	Learn style	Class freq	ExL	ExC	LxC	ExLxC	Avg rank
1	7	–	–	–	+	+	+	–	2.0999999
2	8	+	–	–	–	–	+	+	5.4000001
3	4	–	+	–	–	+	–	+	5.4000001
4	1	+	+	–	+	–	–	–	2.9000001
5	5	–	–	+	+	–	–	+	1.6
6	3	+	–	+	–	+	–	–	4.1999998
7	6	–	+	+	–	–	+	–	6.3000002
8	2	+	+	+	+	+	+	+	3.0999999
	Effect	0.0499999	1.1000001	–0.15	–2.9	–0.35	0.7	2.98E–008	

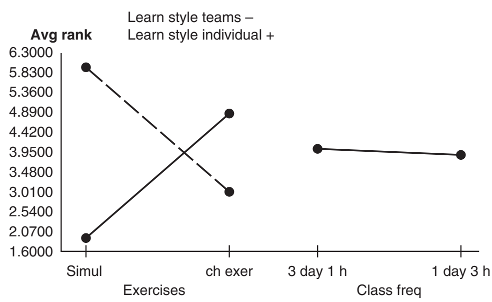


Figure 11.26 Design Matrix and Response Plots for Average Rank in Testing a New Course

	−	Simul	Teams	3day 1hour					
	+	Ch exer	Individual	1day 3hour					
Test	Run order	Exercises	Learn style	Class freq	ExL	ExC	LxC	ExLxC	sd rank
1	7	−	−	−	+	+	+	−	1.2
2	8	+	−	−	−	−	+	+	2.4
3	4	−	+	−	−	+	−	+	1.9
4	1	+	+	−	+	−	−	−	2.5
5	5	−	−	+	+	−	−	+	4.3
6	3	+	−	+	−	+	−	−	3.5
7	6	−	+	+	−	−	+	−	2.9
8	2	+	+	+	+	+	+	+	3.8
	Effect	0.475	−0.075	1.625	0.275	−0.425	−0.475	0.575	

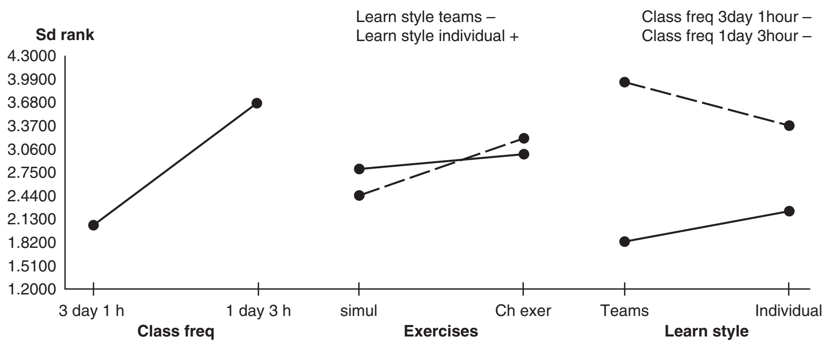


Figure 11.27 Design Matrix and Response Plots for Standard Deviation of Ranks in Testing a New Course

three days per week, the variation in ranks went up. Follow-up questions to the focus group yielded a concern by some going to class three times a week would be difficult while maintaining a part-time job.

Engineering

Having selected the product concepts and defined the product, this phase will test components and systems for the new product. Product specifications must be completed and prototypes tested.

The objectives of testing prototypes are:

- ▲ To confirm that the criteria for function and performance are built into the design.

- To detect likely causes of quality characteristic variation around targets under a variety of conditions.
- To reevaluate costs.

Knowledge of reliability and accelerated testing as well as failure analysis on existing products is essential. The philosophy of testing prototypes should be to challenge the design rather than pamper it. The number of PDSA Cycles used to test prototypes need not be large if sufficient knowledge is gained with each cycle.

Example 11.1 (Continued): Follow-up Study on Interactions

Based on the previous experiment on setting the control factors, the product development team predicts that the new concept will have installation problems with seams. Claims could be high. The plan will be to run another PDSA Cycle with a follow-up study using a new run of material and to learn more about the interactions. The objective of this study was to use a new run of material and determine which interactions persist.

A three-factor experiment was designed with formulation (old and new), preroll, and temperature/humidity as a chunk variable with the low level at both low temperature and low humidity and the high level at both high temperature and high humidity. It was believed that these combinations will create the most extreme conditions as noise factors in the field.

The planning form for the study is given in Fig. 11.28. Visible seams and appearance are the response variables. Appearance will be scored subjectively by an appearance team. A 2^3 factorial design, given in Fig. 11.29, was chosen so that all interactions can be studied.

The run charts for the averages and standard deviations of visible seams at each of the eight combinations are contained in Fig. 11.30. No obvious patterns were present. The effects of the factors computed from the design matrix are included in Fig. 11.29.

The dot diagrams for the average and standard deviation of visible seams are contained in Fig. 11.31. Results are similar to the previous experiment and the dot diagram in Fig. 11.18. Formulation interacted with the temperature/humidity combination to affect the average of visible seams.

1. Objective: Determine the effect control factors and noise factors and their interactions on a redesign for floor covering using a new run of material (follow-up study to the design in Fig. 11.15).		
2. Background Information: Based on the previous experiment with setting the control factors, the product development team predicts that the new concept will have installation problems with seams. Claims could be high. A follow-up study using a new run of material is needed to learn more about which interactions persist.		
3. Experimental Variables:		
A.	**Response variables**	**Measurement technique**
	1. Visible seams (avg, std dev) 2. Appearance	new gage (0.1 mils) subjective scoring by design team
B.	**Factors under study**	**Levels**
	1. Formulation	old new
	2. Temperature/Humidity	50^0/40% 90^0/80%
	3. Preroll	0 min. 10 min.
C.	**Background variables**	**Method of control**
	1. Installer	One person, standard instructions
	2. Type of adhesive	Use standard for all applications
	3. Thickness of intermediate layer	4.0 mils
	4. Thickness of wear layer	1.0 mils
	5. Backing material	Material A (same as old)
	6. Type of floor	Wood
	7. Time material lays flat	4 hours
	8. Cut angle	90^0
	9. Seam layup	Low
4. Experimental Unit: Prototype		
5. Replication: Measurements for visible seams at four positions per sheet		
6. Methods of randomization: Order of the 8 runs was randomized		
7. Design matrix: (attach copy) 2^3 factorial design		
8. Data collection forms: (attach copies) (see Fig. 11.29)		
9. Planned methods of statistical analysis: Run charts, dot diagrams, response plots.		
10. Estimated cost, schedule, and other resource consideration: Evaluated in a test room with temperature and humidity controls. One day is required to complete. Appearance done by team.		

Figure 11.28 Documentation of the Floor-Covering Study

Preroll showed a larger effect on standard deviations of visible seams. Preroll had an effect for the average in Cycle 4 that was not confirmed in this study. The standard deviation response plot showed fewer visible seams with a ten-minute preroll waiting period. The team attributed this to the new run of material. This factor will be watched in future studies.

Test	Run order	1 F	2 T/H	3 P	12	13	23	123	Response Average	Response Standard Deviation
1	3	–	–	–	+	+	+	–	5	8
2	4	+	–	–	–	–	+	+	5	8
3	1	–	+	–	–	+	–	+	10	14
4	7	+	+	–	+	–	–	–	32	16
5	6	–	–	+	+	–	–	+	3	2
6	2	+	–	+	–	+	–	–	10	6
7	5	–	+	+	–	–	+	–	13	8
8	8	+	+	+	+	+	+	+	40	15
Divisor = 4										
Average effect		14.0	18.0	3.5	10.5	3.0	2.0	−0.5		
Standard Deviation		3.2	7.2	−3.8	1.2	2.2	0.2	0.2		

Figure 11.29 2^3 Design Matrix for the Floor-Covering Study

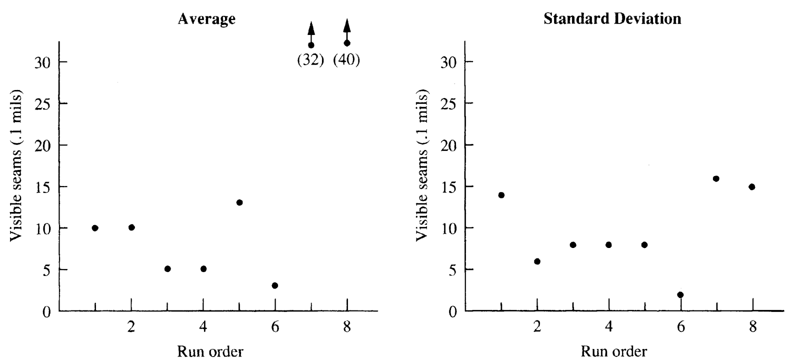


Figure 11.30 Run Charts for the Floor-Covering Study

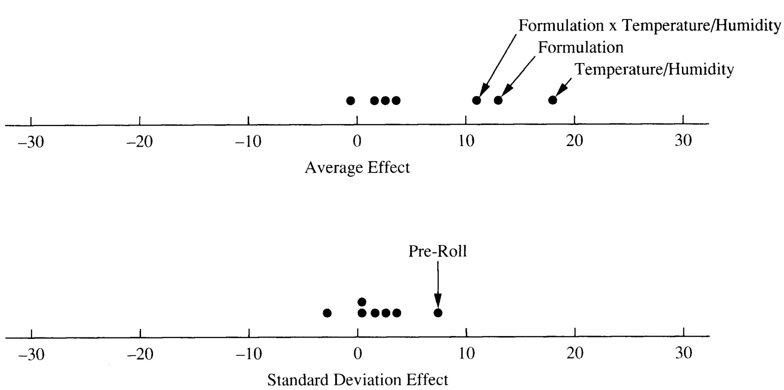


Figure 11.31 Dot Diagram for the Floor-Covering Study

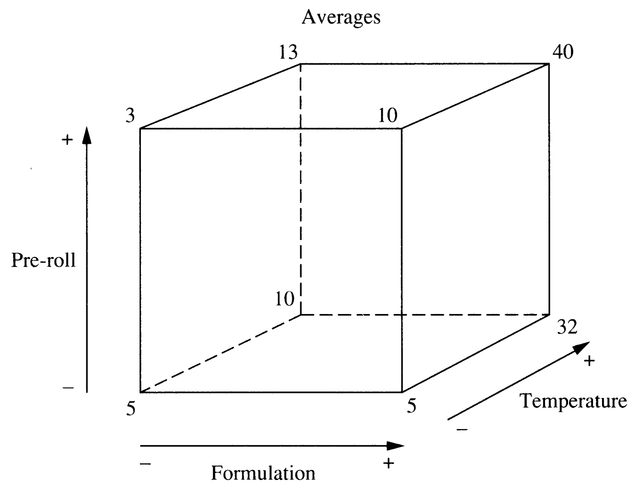


Figure 11.32 Cube Plot for the Floor-Covering Study

Analysis of the cube in Fig. 11.32 revealed the interaction of formulation and temperature/humidity. Response plots for the important factors are given in Fig. 11.33.

The result of this PDSA Cycle was a confirmation of the previous cycle. The team still had a problem with seams. This cycle, however, showed that having the roll to lie flat for 10 min prior to installation reduced the visibility of some of the seams. The team therefore decided that preroll could be controlled as a noise factor by including this finding in the instructions given to the installer.

Because the appearance team had preferred the new product to the old in all other quality characteristics, the team decided to study the effect of some of the control factors on variations in the noise factors identified during installation of the floor covering.

The objective of the next PDSA Cycle was to determine the effect that installation factors had on seams and appearance in a new prototype formulation. The hope was to reduce the effect of noise factors by changing the levels of three control factors:

Factors	Old prototype	New prototype
Wear layer	1.0 mils	2.0 mils
Intermediate layer	Formula 1	Formula 2
Backing layer	Material A	Material B

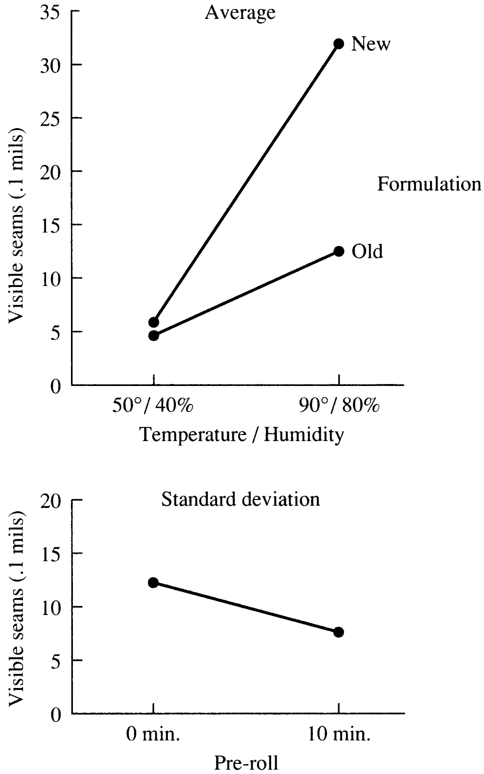


Figure 11.33 Response Plots for the Floor-Covering Study

Hopefully, the new settings for these three control factors would desensitize the product to the temperature/humidity noise factor and the need for a ten-minute preroll.

Figure 11.34 contains the planning form for the study. Three control factors and two installation (noise) factors are studied. Four measurements were made on seams for each sheet, and averages and standard deviations were calculated. A 2^{5-1} design was chosen because there was no confounding of the two-factor interactions.

At completion of the experiment, prototypes were tested for appearance. It was found that appearance of the new design remained good throughout the 16 runs. Laboratory testing for scratches, stains, and gloss retention confirmed the robustness of the new prototype.

Figure 11.35 contains the response plots for standard deviations of visible seams that summarize the important results of the experiment.

1. Objective: Determine the effect of installation factors on a redesign for floor covering by changing three control factors (follow-up study to the design in Fig. 11.28).			
2. Background Information: The redesign has a new color and pattern that has a beautiful appearance. There has been a problem with seams. Probable cause is high temperature or high humidity at the installation site.			
3. Experimental Variables:			
A.	**Response variables**	**Measurement technique**	
	1. Visible seams (avg, std dev)	new gage (0.1 mils)	
	2. Appearance	subjective scoring by design team	
B.	**Factors under study**	**Levels**	
	1. Backing material	Material A	Material B
	2. Formulation of intermediate layer	Formula 1	Formula 2
	3. Thickness of wear layer	1.0 mils	2.0 mils
	4. Temperature/Humidity	50°/40%	90°/80%
	5. Preroll	0 min.	10 min.
C.	**Background variables**	**Method of control**	
	1. Installer	One person, standard instructions	
	2. Type of adhesive	Use standard for all applications	
	3. Type of floor	Wood	
	4. Thickness of intermediate layer	4.0 mils	
	5. Formulation of wear layer	Same as old design	
	6. Time material lays flat	4 hours	
	7. Cut angle	90°	
	8. Seam layup	Low	
4. Experimental Unit: Pre-pilot run			
5. Replication: Measurements for visible seams at four positions per sheet			
6. Methods of randomization: Order of the 16 runs was randomized			
7. Design matrix: (attach copy) 2^{5-1} fractional factorial design			
8. Data collection forms: (attach copies) (not shown here)			
9. Planned methods of statistical analysis: Run charts, dot diagrams, response plots.			
10. Estimated cost, schedule, and other resource consideration: Evaluated in a test room with temperature and humidity controls. Eight days is required to complete. Appearance done by team.			

Figure 11.34 Documentation of the Floor-Covering Experiment

The first plot shows a strong interaction between thickness of wear layer(a control factor)and temperature/humidity (a noise factor). The effect of this noise factor on visible seams is less with the 2.0-mil wear layer. The thinner wear level (1.0 mils) was affected by the high temperature/humidity combination.

The second plot shows a strong interaction between the other two control factors. Backing material and the formulation of the intermediate layer interacted with respect to seams. Because both backing materials are

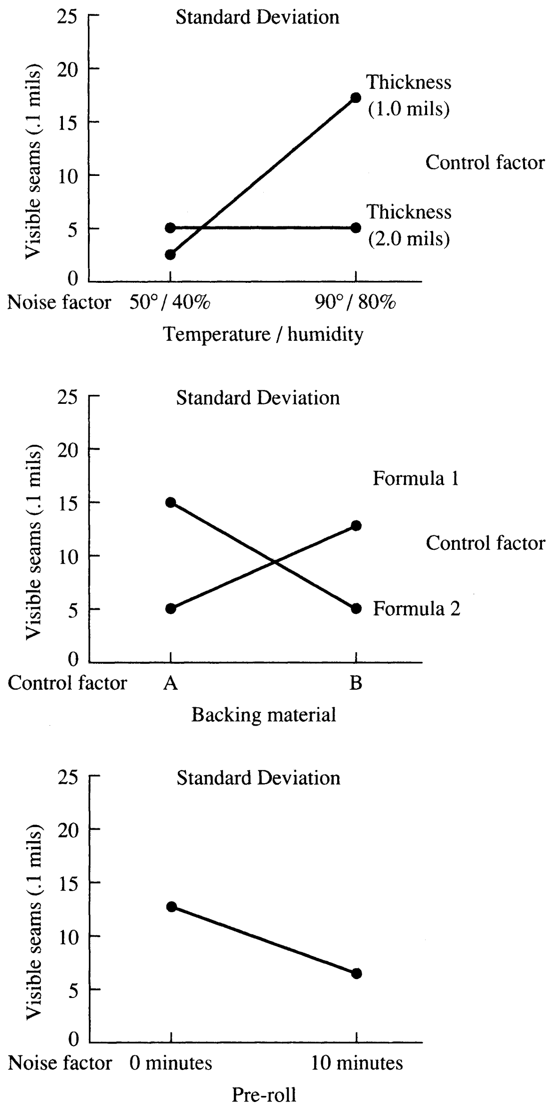


Figure 11.35 Response Plots for the Floor-Covering Experiment

needed for different applications, Material A is chosen with Formula 1 and Material B is chosen with Formula 2.

The third plot demonstrates a strong relationship between an installation factor and visible seams. By laying out the roll for 10 min before installation, the seams will have less variation. This adds to the installation time.

Based on these analyses and the team's current knowledge, the following conclusions are:

Control factors	Best setting
Thickness of wear layer	2.0 mils
Backing Material A	Formula 1
Backing Material B	Formula 2
Noise factors	**Method of control**
Preroll	Have installation instructions include a 10-min preroll step.
Temperature/humidity	Desensitized by setting the thickness of wear layer control factor at 2.0 mils.

Updates to the QFD relation diagram are given in Fig. 11.36.

The team next had to design the production process. No new equipment was needed for the production process. Backing Material B was new and required a new supplier. The increase in wear thickness to 2.0 mils increased costs. This increase was offset by the lower cost of backing Material B.

Training based on the change to the production process was conducted for all those involved. Short production runs indicated no new production problems. The changes made in the redesign of the product did not result in any difficulties for the production process.

The team had decided to proceed with a pilot run of samples for each of five basic color/pattern product types. Formulation for each type of color/pattern was as follows:

Product type (color/pattern)	1	2	3	4	5
Backing material	A	A	A	B	B
Formula	1	1	1	2	2

Backing Material A was chosen for the first three product types because of the successful use of that material for other current product types similar to them.

QFD Relation diagram for quality characteristics and factors for design

- [x] design of product: system floor covering
- [ ] design of product: component of the system
- [ ] design of process:

	Quality characteristics	Target	Color	Pattern	Backing Material	Formulation of Intermediate Layer	Thickness of Intermediate Layer	Formulation of Wear Layer	Thickness of Wear Layer	Amount Embossing	Type of Wall	Usage	Temp. Installation	Humidity Installation	Time Material Lies Flat	Pre-Roll	Cut Angle	Seam Layup
			control factors								noise factors							
1.	Consistent with fashion trends	Smaller is Better	⊙	⊙		○		○	△	○								
2.	Attractive	Bigger is Better	⊙	⊙		○		○	△	○	△	△						
3.	Visible seams	Smaller is Better			⊙	⊙	⊙	△	⊙	△	△		⊙	⊙		△	△	△
4.	Time to clean	Smaller is Better						⊙	⊙	○		⊙				△	△	
5.	Effort to clean	Smaller is Better		△				⊙	⊙	⊙		⊙				△	△	
6.	Resistance to scratches	Smaller is Better				△	△	⊙	⊙	⊙		⊙						
7.	Stain resistance	Smaller is Better	○	△				○	○	⊙		⊙						
8.	Gloss retention	Bigger is Better	△	△				○	○	⊙		⊙						
		best setting / method of control	Use all	Use all	Material A, Formula 1	Material B, Formula 2			2.0 MILS		None required	None required	Thickness wear layer at 2.0 Mils	Thickness wear layer at 2.0 Mils	Instructions at installation	Instructions at installation	None required	None required

⊙ = high
○ = medium
△ = low

What planned experiments need to be run to test this diagram? 2^{8-4} cycle 3, 2^3 cycle 4, 2^{5-1} cycle 5

Figure 11.36 Updated QFD Relation Diagram for Redesigning Floor Covering

Operations

How are the best operating conditions for a manufacturing process chosen from the hundreds of possibilities? The strategy of robust design discussed for engineering in Phase 1 applies directly to developing and testing the production process. The leverage for improvement of quality is in reducing variation of the quality characteristics of the product due to unit-to-unit noise (variations in the manufacturing process).

The control factors for the product usually become the quality characteristics for the manufacturing process. After selecting the concepts for the production process (there are cases when a new concept for production process may not be necessary), the next step is to select factors for designing the production process. The QFD relation diagram should be used again with the control factors and noise factors coming from the production process.

The aim of robust design in operations should be to set control factors that will improve process capability by reducing the effect of noise factors (highest leverage for unit-to-unit noise).

Examples from previous chapters will illustrate this strategy as it applies to designing the production process.

Example 3.5 showed that the control factor, application rate, resulted in the smallest percentage of loose labels when the target was 14 oz/h. This factor interacted with a chunk variable (one or more background variables) used to define the block. Interaction was used to desensitize the product. A follow-up study would be a factorial design to study the background variables used to make up the chunk variable.

Example 4.2 has a shade of a dyed material as the quality characteristic. The target is at shade 200. The factorial design showed that running the process at high oxidation temperature makes the process less sensitive to variation in the material. The third factor, oven pressure, can be used to adjust the shade to 200.

Example 9.2 has fill weight as a quality characteristic. A number of factors that affected the average fill weight had been identified. A factorial design with a center point was run with fill weight variation to determine the presence of nonlinear effects. The results shown in Chap. 9 indicate a nonlinear response with line speed. If speed is kept below 350 cans per hour, the variation in fill weight will be less. Also, temperature and consistency interact. Keeping temperature above 200°C minimizes the variation in fill weight due to varying consistency of the incoming ingredients.

Process definition is the output of this process design phase. The next step is to standardize things or methods that have already been found to be good (standard parts, units, or modules, and standard procedures).

Development of production capability and development of the product must be done in parallel. This ensures smooth and efficient transition into factory operations, for product and production design must be managed together.

Having applied the strategy of robust design to designing the production process, the next step is to validate that the production process produces good product. Specifications and tolerances help to define acceptable outcomes.

There are different approaches to the management of variability resulting from the production process. The aim should be to reduce the dependence on inspection to achieve quality. The purpose of inspection should be for improvement of process and reduction of costs. Mass inspection is costly and ineffective. The application of the Model for Improvement and the methods of control charting and planned experimentation provide the basis for the control plan. See Chap. 8 for more use of control charts.

Production capability must be developed to produce the parts and components, to assemble the product, and to have operating systems that are necessary for production and field operations. Building prototypes confirms the product. Often parts and components are handmade. Pilot runs with production tooling confirm the process. During a pilot run, products from the production process are studied for the first time. A pilot run also provides the opportunity to predict future production capability. The methods of control charting and determining the capability of a process are useful here.

What are the important control factors? What are the noise factors that the product might encounter during production? Pilot runs provide the opportunity to establish the relationships between the control factors, noise factors, and quality characteristics as identified by the QFD relation diagram for the production process. Planned experimentation will increase the knowledge of these relationships. This will help establish the best operating conditions for the manufacturing process before production starts.

Example 11.1 (Continued): The Field Test for New Floor Covering

The objective of this PDSA Cycle was to field-test the pilot run of floor covering. All five product types from the pilot run were evaluated along with the old product. A field test was chosen over the temperature and humidity environment of the R&D lab.

This cycle must increase understanding of performance of the new design with respect to potential problems. Including the old product with the pilot product of the new design under widely varying conditions should increase the team's degree of belief about its future predictions of product performance.

Field sites were used to create a blocking factor. The blocks chosen were judged likely to create extreme conditions. Figure 11.37 gives the planning form for the study.

1. Objective: Determine the performance of a redesign for floor covering under various field conditions. This information will be used to determine if the new product should go to production.

2. Background Information: Previous experiments have lead to changes in the current design. Noise factors during installation are affecting the variation in visible seams.

3. Experimental Variables:

A.

Response variables	**Measurement technique**
1. Visible seams (avg, std dev)	new gage (0.1 mils)
2. Appearance	subjective scoring by design team

B.

Factors under study	**Levels**
1. Product types	1 2 3 4 5 6 (old product)

C.

Background variables	**Method of control**
1. Type of adhesive	Use standard for all applications
2. Time material lays flat	2 hours
3. Cut angle	Standard at 90°
4. Seam layup	Set at low
5. Preroll	Instructions (10 min)
6. Thickness of wear layer	Measure

Method of control for all other background variables: Create four blocks (field sites) made up of different treatment combinations of background variables.

Background factor	Block 1	Block 2	Block 3	Block 4
1. Field site	N.E.	N.W.	S.E.	S.W.
2. Humidity	middle	low	high	low
3. Temperature	middle	low	high	high
4. Floor	wood	old	cement	old

4. Experimental Unit: Pilot run

5. Replication: Measurements for visible seams at four positions per sheet

6. Methods of randomization: Order of the 6 levels within block was randomized

7. Design matrix: (attach copy) (not shown here)

8. Data collection forms: (attach copies) (see Fig. 11.38)

9. Planned methods of statistical analysis: Run charts for the six sample types adjusted for block effect.

10. Estimated cost, schedule, and other resource consideration: Field testing will require thirty days to complete.

Figure 11.37 Documentation of the Floor-Covering Experiment

Response: standard deviation of visible seams (run order in parentheses)

Product	Block 1	Block 2	Block 3	Block 4
1	(3) 2	(2) 4	(6) 12	(3) 5
2	(4) 7	(4) 6	(1) 9	(1) 7
3	(6) 2	(5) 12	(3) 12	(5) 1
4	(1) 9	(1) 6	(2) 14	(2) 10
5	(2) 7	(3) 4	(4) 10	(4) 8
6 = old	(5) 9	(6) 10	(5) 12	(6) 11

Figure 11.38 Test Results for Floor-Covering Study

The results for the standard deviation response variable are given in Fig. 11.38. A run chart for standard deviation of visible seams is given in Fig. 11.39.

The run chart in Fig. 11.39 confirmed the results of the previous cycle. Standard deviations for visible seams are 14 or less. The pilot run of five product types compared favorably with the old product types. The team predicted that claims against the redesigned product will not exceed claims against the old product.

For all five product types, appearance exceeded the old product at all four field sites. The action of the team was a decision to start production of the redesigned floor-covering product. Production continued to run the pilot for four days to determine capability of the processes.

11.5 Phase 3: Produce Product

The major tasks in this phase for marketing involve providing sales and service and establishing a customer feedback system. The product designers

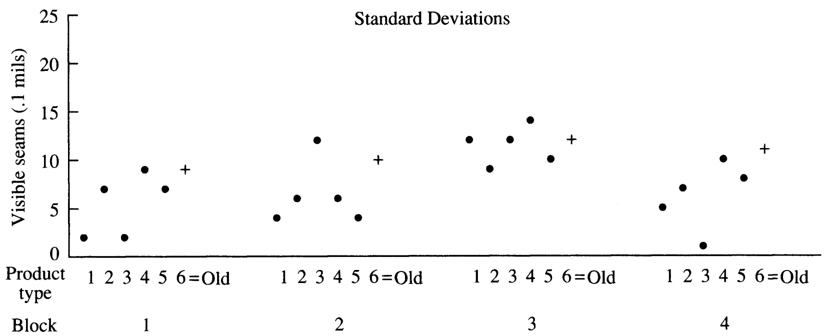


Figure 11.39 Run Chart for Block Design of Floor-Covering Study

need to support the product in production and the field. Operations are involved with producing the product and addressing any problems associated with production. All functions should be involved with any improvement activities associated with the product. Most of the examples in Chaps. 3–10 represent these improvement activities.

11.6 Summary

This chapter illustrated the importance of well designed and executed experiments to aid in designing quality into new products (processes or systems). The development started with Deming's conception of production as a system and the emphasis on the design and redesign stage in matching products and services to a need.

A four-phase process in the design of a new product was presented. The key tasks of this process included defining quality, setting targets, and designing products or processes that are close to the targets under a wide range of conditions.

By integrating the concepts of quality function deployment (QFD), the ideas developed by Taguchi, and the methods of planned experimentation into the Model for Improvement, a strategy or road map for quality by design is created. Application of this strategy can:

- Accelerate the evolution of new product cycles.
- Reduce development costs.
- Improve the transition from R&D to manufacturing.
- Make the product or process robust against noise factors by selecting the proper level of control factors. This results in higher acceptance of the product and less warranty claims.

The role of each of the major functions (marketing, engineering, and operations) with respect to planned experimentation is summarized below:

Objective of Experiment

Marketing: Determine the best features that would satisfy the customers' needs and wants.
Engineering: Select the best factors for design of product.
Manufacturing: Select the best factors for design of the production process.

Response Variables:

Marketing: Preference ranking by potential customers.
Engineering: Quality characteristics derived from customer needs
Manufacturing: Product specifications

Factors Under Study:

Marketing: New product features
Engineering: Factors for design of product
Manufacturing: Factors for design of production process

Finally, applying these strategies of experimentation to the design of a new product provides the greatest leverage for improvement of quality.

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Exercises

11.1 Study the effect of poor quality product design and production process design for products in an organization. (Use warranty claims and work backward.)

11.2 Compare the processes in an organization with those in the evolution of a new product from Fig. 11.1.

11.3 Identify the three sources of product performance variation (external, internal, and unit-to-unit) for the major products in an organization.

11.4 Complete a QFD relationship diagram for a new or existing product.

11.5 Determine how many planned experiments were carried out by product design engineers or manufacturing engineers in an organization in the last two years.

11.6 The paper box factory. Design a paper box that stores change (quantity equal to the change in most people's pockets). Materials and technologies include:

Two pair of scissors
Two small staplers
Four crayons
A ream of 8½ in. × 11 in. blank paper

Appoint a product planning team, a product design team, a production process design team, a manufacturing team, and a marketing team.

Use the four-phase process from Fig. 11.1 to develop your product and production processes. What are the customer needs? (The box needs a removable lid.) What are the quality characteristics? What is your measurement process? What are the product control factors? Noise factors?

Manufacturing should produce 50 boxes. Is the process stable? Capable? Can the product be improved? How? Can the process be improved? How?

11.7 Study Example 11.1 on designing a new floor covering throughout the chapter. Discuss possible alternative approaches to the design and analysis of data. Discuss why this example involved analytic studies. Were there any enumerative aspects of this example?